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APPLICATION OF THE LOCAL ANALYSIS AND PREDICTION SYSTEM (LAPS) DIABATIC INITIALIZATION OF MESOSCALE NUMERICAL WEATHER PREDICTION MODELS FOR THE IHOP-2002 FIELD EXPERIMENT

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1. INTRODUCTION

The NOAA Forecast Systems Laboratory's (FSL) Local Analysis and Prediction System (LAPS) (Albers et al., 1996) has been enhanced over the last few years to provide a capability for initializing mesoscale numerical weather prediction models with clouds and precipitation present in the initial conditions (Shaw et al., 2001). This diabatic initialization procedure has been referred to as the "hot start" technique.

The basic technique involves the use of the three-dimensional LAPS cloud analysis, which includes all microphysical species to diagnose estimated vertical velocity profiles based on cloud type, depth, horizontal scale, and stability criteria (Schultz and Albers, 2001). These estimates are then used as constraints in a three-dimensional variational (3DVAR) step along with a first-guess field, the LAPS univariate temperature, moisture, height, and wind analyses to develop model initial conditions that are in dynamic balance with the observed cloud field while maintaining consistency with the observations. The LAPS method of balancing the dynamic fields with the cloud analysis is more fully described in McGinley and Smart (2001). What makes LAPS unique in this application is its ability to use virtually all operationally available sources of meteorological information, including wideband WSR-88D data and GOES imagery, in a computationally efficient manner.

This technique has been used in mesoscale NWP models at FSL to improve explicit short-range forecasts of clouds and precipitation since the summer of 2000 (Shaw et al., 2001). During the summer of 2002, this technique was used to initialize a nested MM5 domain at 12-km grid spacing for the outer grid and 4-km grid spacing for the inner grid (Fig. 1). The grids were made available to forecasters supporting the IHOP field operations via FSL's FX-Net client software. Additionally, the quantitative precipitation forecasts (QPF) were verified against point observations and the NCEP Stage IV precipitation analyses via FSL's Real-Time Verification System (RTVS) (Mahoney et al., 2002).

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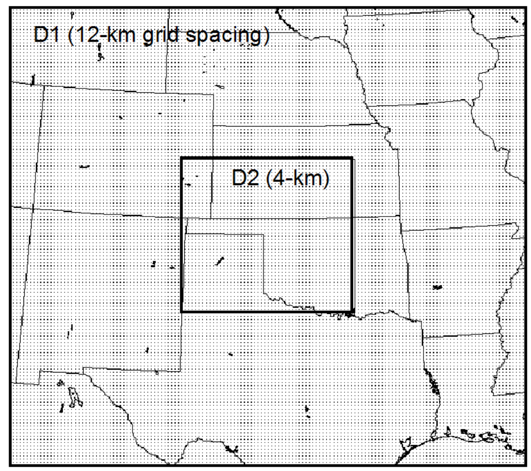

Fig. 1. MM5 domain used for the IHOP field experiment. Grid-spacing on the outer domain is 12 km. The inner nest (box in center of figure) utilized 4 km grid spacing.

Since the conclusion of the real-time portion of the IHOP campaign, FSL researchers have been evaluating the forecasts objectively and subjectively. Additionally, FSL is in the process of re-running all of the 12-km MM5 forecasts covering the IHOP experiment period originally verified via RTVS using LAPS initial conditions that were improved as a result of lessons learned during IHOP. For every MM5 case being regenerated, FSL is also performing simulations with the same initial and lateral boundary conditions, but using the Weather Research and Forecast (WRF) model as the predictive component. Finally, for some specific case studies involving the evolution of the low-level jet and associated moisture transport, LAPS-initialized WRF simulations are being utilized to aid understanding of the key processes involved.

The archive of operational and research data available from IHOP-2002 provides an excellent opportunity for testing improvements to the LAPS diabatic initialization and the associated mesoscale models as we strive to improve our ability to explicitly forecast convective initiation, storm-scale evolution, and precipitation amounts using high-resolution NWP models. This paper provides an overview of the results from the real-time experiments as well as preliminary results from the ongoing post-experiment research.

2. REAL-TIME USAGE

2.1 Configuration

MM5 was run at FSL on a 20-node Linux cluster every three hours. Each forecast extended to 12 hours and provided hourly output. Incremental post-processing was performed concurrently, so products from the model were available to forecasters before the simulation was complete.

The outer grid was initialized with LAPS, and the inner nest obtained its initial conditions via interpolation from the outer grid. One-way nesting was utilized, so the inner grid's solution was not fed back to the outer grid. The Kain-Fritsch convective parameterization was employed on the outer grid, while the inner domain remained fully explicit for convective processes. For both domains, the Schultz (1995) microphysics scheme was selected because of its computational efficiency and compatibility with the LAPS cloud analysis. The MRF boundary layer scheme was used in conjunction with the five-layer soil model. Longwave radiation was handled via the RRTM scheme. The time step was 30 seconds.

Model output was transmitted in GRIB format in real-time to an Automated Weather Interactive Processing System (AWIPS) data server. Once on the data server, forecasters supporting the IHOP field operations in Norman were able to view the forecasts via the FX-Net client software. Additionally, these GRIB files were used by RTVS to perform the quantitative evaluation of the precipitation forecasts.

2.2 Results

The IHOP campaign provided the first intensive evaluation of the LAPS hot-started MM5 for convective weather situations. Prior to this experiment, most of the evaluations had been done for winter cases. As such, new challenges were identified for the LAPS initialization procedure.

Early in the experiment, it was readily apparent from forecaster feedback that the model was significantly over-forecasting precipitation in the early hours. At that time, two issues were suspected to be at the root of this problem. First, to prevent evaporation of the model clouds inserted by LAPS during the first few steps of model integration, the LAPS analysis saturated all grid boxes containing cloud water, regardless of the amount of cloud water present. This was adding significant amounts of total precipitable water to the column. Second, no limit was being applied to the amount of cloud water and ice being diagnosed by the LAPS analysis. In practice, however, one needs to be cognizant of how the microphysical scheme being employed within the forecast model operates. In this case, there were instances when the amount of cloud water and ice far exceeded (by one to three orders of magnitude) the threshold used by the Schultz microphysics for starting the liquid to rain and ice to snow conversion processes.

Subsequent investigation during the post-experiment phase revealed another problem in the LAPS initialization that appears to have been a major contributor to the over-forecasting of precipitation. Within the LAPS procedure that balances the dynamic fields to the cloud analysis, a warm bias throughout the column was being introduced. In the mid-levels of the atmosphere, this bias was as much as 2-3 K. Combined with the saturation condition applied for cloudy grid boxes (increases overall moisture content), this was leading to a destabilization of the simulated atmosphere and a subsequent increase in the amount of precipitation forecast. This problem and results of correcting it are discussed further in Section 3.

The model forecasts had problems simulating elevated convection, which was frequently present in the domain during the morning hours. This was addressed in the LAPS initialization by changing the depth of the vertical motion profile to only consider the actual depth of the cloud. Prior to IHOP, the base of the upward vertical motion was assumed to be below the cloud by 1/3rd of the cloud depth.

During the IHOP operational periods, much emphasis was placed on the analyses and NWP forecasts of mesoscale and synoptic scale boundaries that could potentially play a role in convective initiation. Generally, forecaster confidence was high in the ability of the LAPS MM5 forecasts of dryline and other frontal positions. One deficiency noted, however, was the propensity for MM5 to generate excessively strong and long-lasting outflow boundaries from simulated convective cells. This may be due to the evaporation constants used within the Schultz microphysics being tuned for smaller droplet sizes than what is typically found in deep convection in the IHOP region, which would produce anomalously large amounts of evaporative cooling compared to reality. A detailed evaluation based on forecaster feedback is contained in Szoke et al. (2004).

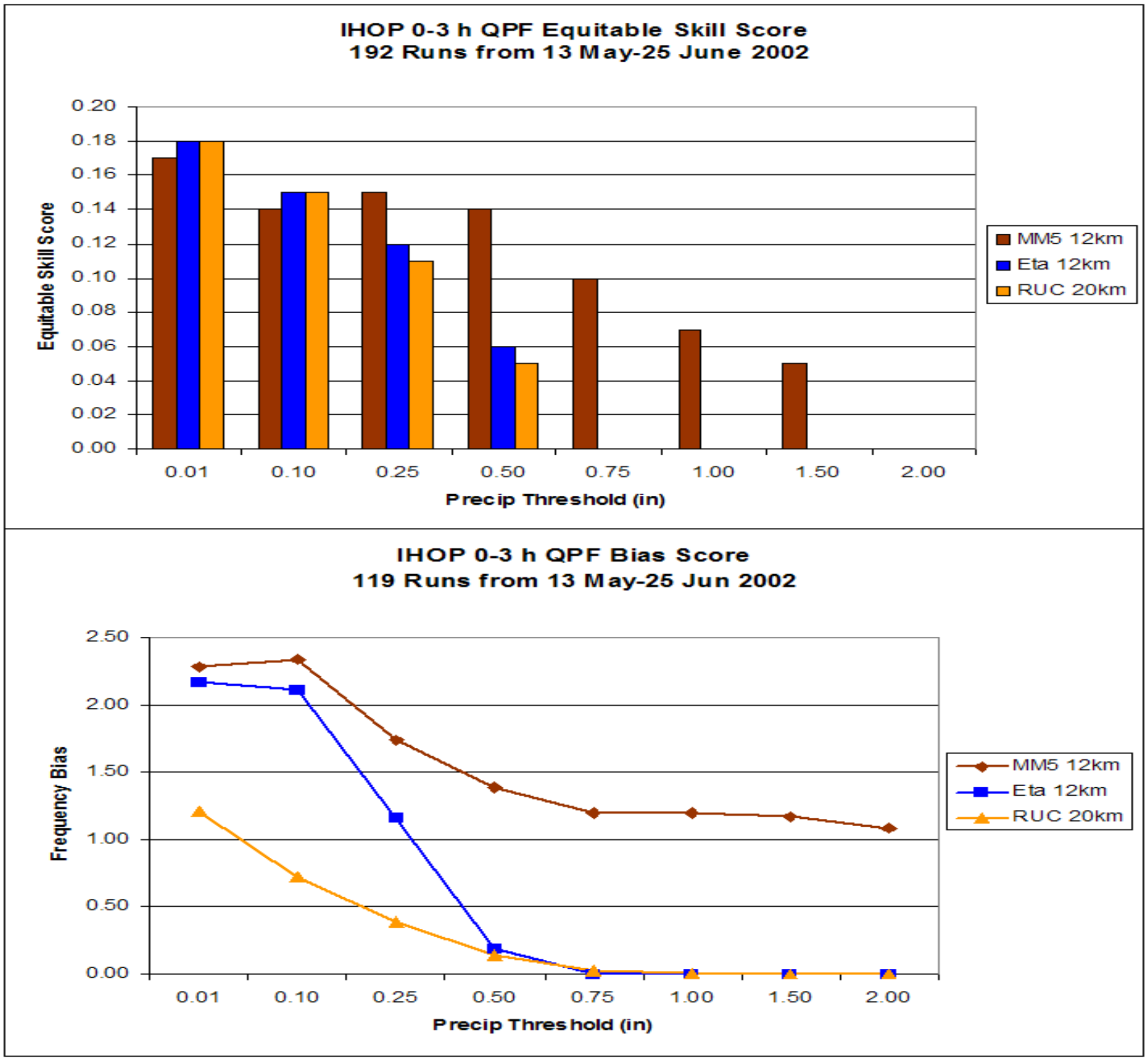

Fig. 2. Equitable skill score (ESS, top) and frequency bias (bottom) for the 12-km MM5, the operational 12-km Eta, and the FSL 20-km RUC 0-3 h quantitative precipitation forecasts (QPF). Statistics cover the entire IHOP campaign period, and were generated using the FSL Real-time Verification System (RTVS).

Despite the shortcomings discussed above, the real-time, LAPS-initialized MM5 forecasts demonstrated significant improvement in forecast skill for short term precipitation forecasts when compared to the national models. Fig. 2 shows the equitable skill score and frequency bias for the 3-h QPF for forecasts from the 12-km MM5, the operational 12-km Eta from NCEP, and the experimental 20-km RUC run at FSL for the entire duration of the experiment. The MM5 demonstrated a distinct advantage for all precipitation thresholds, particularly for the higher thresholds. In the case of the thresholds above 0.50 in, the MM5 was the only model that demonstrated any positive skill.

Fig. 3 shows the same set of statistics, but only for the period beginning after 25 May, when a change was implemented in LAPS to reduce the high bias of precipitation. Prior to this point, all species of condensate (cloud liquid, cloud ice, rain, snow, and graupel) were present in the initial conditions from LAPS. Additionally, for every grid box in the three-dimensional volume that contained cloud liquid, the relative humidity was raised to 100% to provide a saturated condition for the model microphysics. The intent of the saturation was to prevent rapid evaporation and subsequent downdrafts in the presence of clouds. However, it was determined that this artificial saturation condition was adding significant amounts of moisture to each column. Thus, beginning on 25 May, the saturation condition was removed.

Additionally, the amount of cloud condensate allowed in the model initial condition was reduced by scaling the LAPS values by 0.5. These changes were intended to provide a “quick fix” to the over-

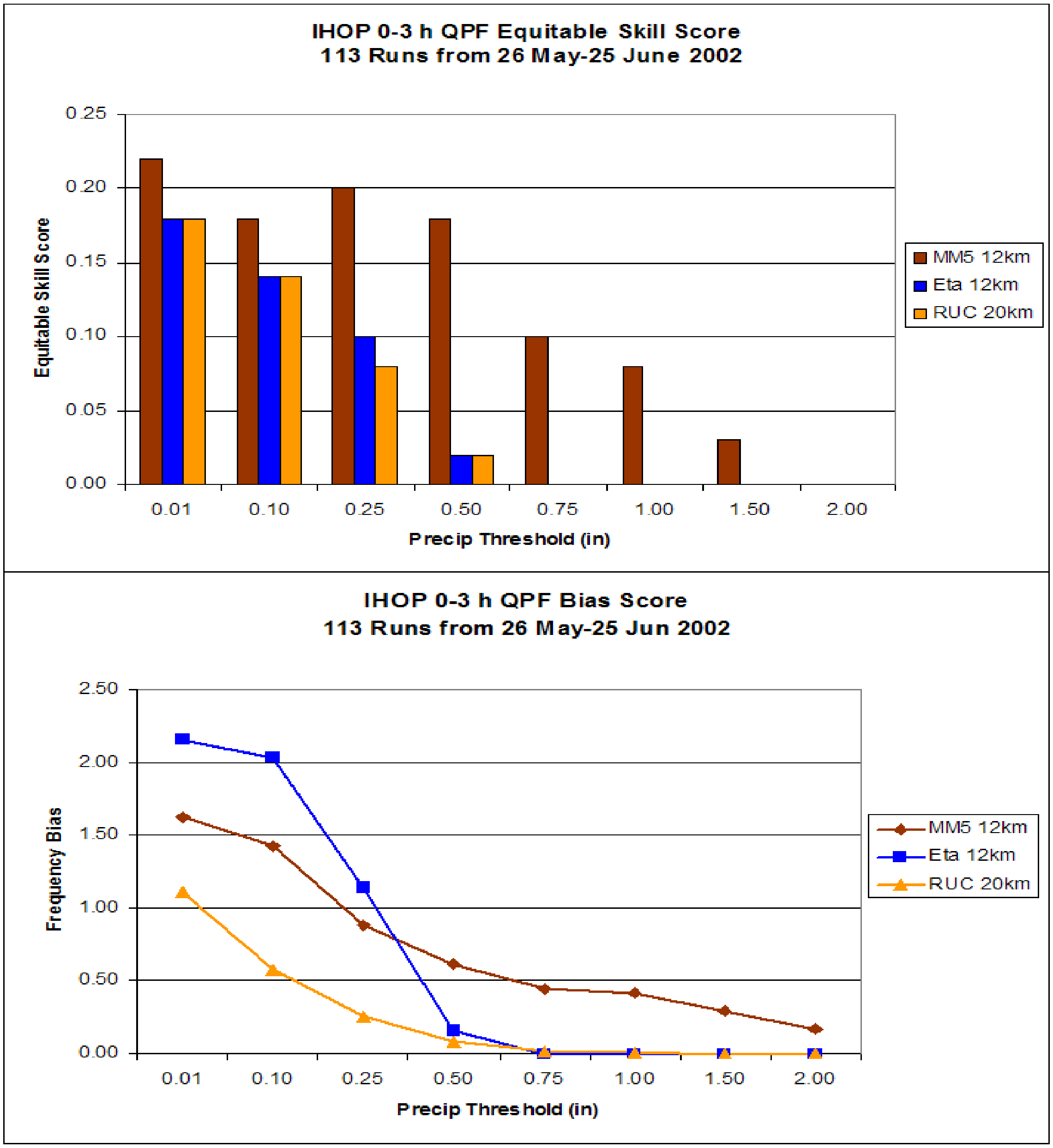

Fig. 3. Same as Figure 2, but for a shorter period beginning 26 May 2002 after some quick-fix corrections were applied to the LAPS initialization in an effort to reduce the high QPF bias in the early hours.

prediction of rain while the problem continued to be investigated. Fig. 3 does show a significant decrease in the bias as well as a corresponding increase in skill. However, no detailed analysis has been done to compare the weather regimes prior to and after 25 May to see how much of the difference could be accounted for by changes in the weather patterns.

Although the bias and skill scores improved after these changes, subjective evaluation of the forecasts indicated that the model was suffering from "spin down" in the early hours of the forecast for the remainder of the experiment. It was noted frequently that the initial conditions would have an excellent representation of convective weather in progress, but during the first hour of model integration, these simulated cells would rapidly dissipate and redevelop later, rather than maintaining themselves similar to what actually occurred. Several minor adjustments were made during the remainder of the experiment to address the spin-down problem, but very little impact was noted. This problem became the focus of the research during the post-real-time phase of the project.

In spite of the difficulties, the results from the real-time phase seem to support the notion that short-term prediction of convection and rainfall amounts can benefit from the use of a mesoscale model combined with the LAPS diabatic initialization, especially for the 0–3 h QPF. The MM5 forecasts also demonstrated significantly better skill for the 0–6 h QPF (Fig. 4). For the 12 h QPF, the skill advantage was negligible, and the operational Eta matched or exceeded the MM5 skill for most categories. This is likely due to the effect of the lateral boundary conditions (which were provided by the Eta model) becoming the dominant

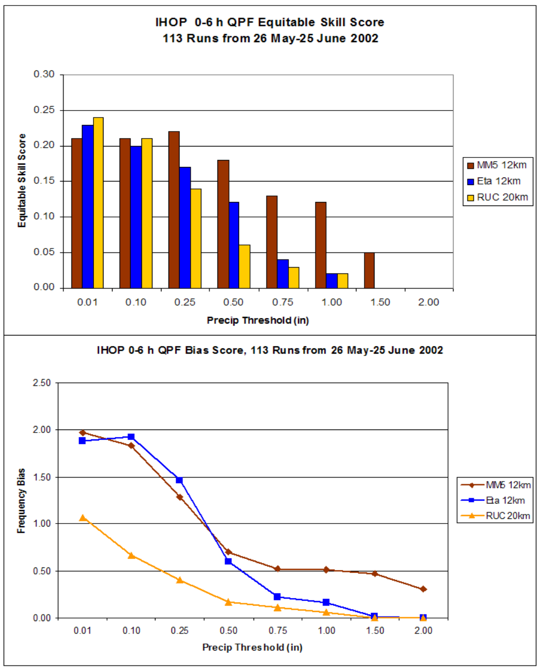

Fig. 4. Same as Fig. 3, but for the 0-6 h period.

source of the model forcing for this limited area domain.

It is also interesting to note that the bias values of the MM5 precipitation forecasts gradually increase with forecast length (Fig. 5), particularly after 6 h. This growth in the precipitation bias has been observed in MM5 forecasts for other projects at FSL, and is independent of the initialization method used for the mesoscale model.

The demonstrated advantage in forecast skill of the LAPS-initialized MM5 is consistent with previous studies for winter cases. Although the absolute scores are lower than those observed for the winter cases, the relative improvement compared to the national models is significant.

3. POST-EXPERIMENT RESEARCH

Since the conclusion of the real-time portion of IHOP, FSL has focused on using the archived LAPS analyses and forecasts produced during the

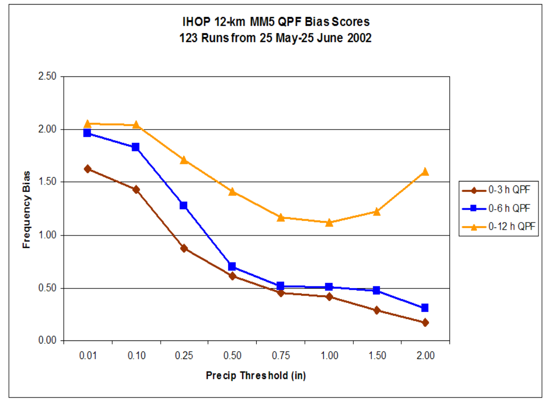

Fig. 5. QPF frequency bias for the 0-3 h, 0-6 h, and 0-12 h 12-km MM5 forecasts.

period as a test bed for changes to the LAPS diabatic initialization. Specifically, the research has focused on improving the quantitative precipitation forecasts from MM5 and WRF through changes to the LAPS treatment of the cloud analysis and balance condition. The changes being developed and tested are more rigorous and more physics-based than the crude “quick fix” changes implemented during the field phase of IHOP.

For this phase, a strategy was developed to re-run all of the simulations that were verified via RTVS during the experiment. Although real-time runs were produced every 3 h, only the runs with 0000, 0600, 1200, and 1800 UTC initial times were verified, so these are the cases being reproduced. Furthermore, only the 12-km grid is being utilized for this initial research. These new simulations are referred to as the “routine” cases. For all of the routine cases, both MM5 and WRF are being used.

In addition to the routine cases, a select number of additional cases to support other efforts at FSL are being reexamined. These cases involve detailed research on the structure and evolution of the low-level jet and on the development, structure, and evolution of two bore cases observed during the experiment. In these special cases, the use of the WRF model is emphasized. The focus of this paper, however, is on the results of the routine simulations.

3.1 Model Configuration

For the routine simulations being regenerated, the configuration used for MM5 is nearly identical to the original real-time configuration, except that the OSU Land Surface Model package is now being used. To initialize the soil moisture and temperature fields for this package, the NCEP Eta grids are being used.

The WRF model configuration has been selected to mimic the MM5 configuration as closely as possible. The WRF has multiple dynamic cores available, and the one selected for the IHOP research is the Eulerian Mass core developed at the National Center for Atmospheric Research (NCAR). The primary difference between the MM5 and WRF configuration is the microphysics package. For the WRF simulations, the NCEP 5-class option is used since the Schultz algorithm is not available within WRF. The time step for WRF model integration is also set to 60 s instead of the 30 s used for MM5. This is possible due to the third-order Runge-Kutta dynamic solver used within the WRF model.

3.2 LAPS Changes

LAPS is undergoing continuous development and change. The focus of this research relates to specific changes to the initialization of NWP models, including the specification of the hydrometeor concentrations, the associated cloud vertical motions, the dynamic balance package, and the adjustment of the relative humidity with respect to the hydrometeor fields. Significant changes in these areas include:

- Improved treatment of moisture within the balance package to conserve specific humidity. An adjusted relative humidity value is now computed based on the balanced temperature field and the original analysis of specific humidity (which has already considered the cloud analysis)

- Tuning of the cloud vertical motion profiles to account for grid spacing dependencies. The depth of the parabolic updraft profile for convective clouds has been reduced to improve treatment of elevated convection. The peak updraft value has now been made a function of grid size used by the model domain. Prior to this, the peak updraft values were only a function of cloud depth and type.

- Limitations on peak values of the hydrometeor concentrations based on grid spacing and the auto-conversion rates of liquid to rain and ice to snow used in the model being initialized. For now, the values used are tuned for the Schultz microphysics for both the MM5 and WRF simulations, even though WRF is utilizing the NCEP 5-class scheme.

- A slight amount of super-saturation is now applied to grid boxes containing a minimum threshold of cloud liquid and/or cloud ice. In the case of cloud liquid, the saturation vapor pressure is computed with respect to liquid. If only ice is present in the appropriate threshold, then the saturation vapor pressure is computed with respect to ice. In either case, the value of relative humidity used in this situation is 102% (with respect to either liquid or ice). Slight super-saturation is allowed to offset reductions in the relative humidity due to the grid point averaging that occurs during the staggering of the data from the analysis grid to the model mass-point grid.

The goal of the diabatic initialization is to provide an accurate and stable representation of the cloud and precipitation processes as the mesoscale model would represent these features for a given resolution, hopefully thereby improving forecasts of short-term precipitation. The purpose of the routine re-runs for the IHOP cases is to test the changes made to LAPS to better meet this goal over a statistically significant number of cases.

3.3 Results

Applying the previously discussed changes to the model initialization required reprocessing all of the 6-hourly LAPS analyses on the 12-km grid for the IHOP period from 13 May through 25 June 2003. Unfortunately, missing data in the archive of IHOP LAPS analyses were discovered. At the time of this writing, FSL staff were working on reproducing the LAPS analyses for the missing times. In spite of this, 110 routine simulations have been made with MM5 and 108 with WRF. The simulations were processed by RTVS, allowing for a direct quantitative comparison between the original MM5 simulation (MM5_Op), the re-run of MM5 (MM5_RR) using the improved LAPS analysis, and the WRF, also using the improved LAPS analysis. For the 108 simulations for which all 3 of these models were available to RTVS, point verification of the 3 h, 6 h, and 12 h precipitation forecasts indicate that the LAPS improvements have had the desired effect of reducing or eliminating the large positive bias of forecast rainfall observed during the real-time phase of the experiment. The 6 h QPF verification from RTVS is shown in Fig.6. In terms of the equitable skill score (ESS), the improvements are small and even insignificant for some thresholds. However, the bias scores are much improved. For the lower thresholds, the MM5_RR forecasts are actually under-biased, yet still producing a better ESS. One curiosity is the behavior of the bias score for the MM5_RR, which increases with increasing threshold. This is opposite of all of the other forecast models, including the original MM5_Op simulations.

An encouraging result for the mesoscale NWP community is the performance of the WRF model, which has the best ESS for all except the highest category (1.0 in) shown in Figure 6. Additionally, the bias score of the WRF is more consistent across all thresholds than either the MM5_Op or the MM5_RR. Considering that WRF is not yet officially even declared to be a research grade model, it is performing surprisingly well, even without much “tuning” in preparation for the IHOP application.

After the initial set of routine re-runs were completed, a significant problem with the LAPS balanced temperature analysis was discovered. A positive temperature biase was being introduced throughout the three-dimensional volume. This bias was typically 2-3 deg C, and led to destabilization of the NWP model and usually an over-prediction of clouds and precipitation. This problem was present in both the original MM5_Op runs performed during the real-time phase as well

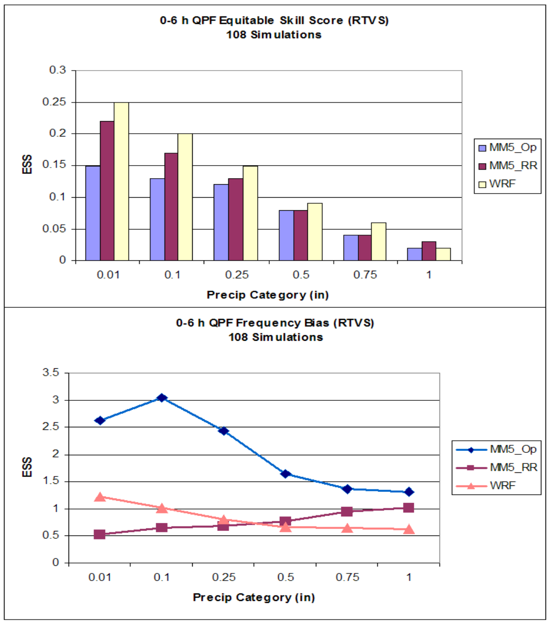

Fig. 6. Comparison of the original MM5 forecast (MM5_Op) to the MM5 rerun (MM5_RR) and WRF, both of which used the improved LAPS analysis.

as the MM5_RR and WRF simulations.

This problem has since been corrected, and there are plans to again reproduce a new set of MM5 and WRF simulations. To date, a subset of the simulations has been rerun for MM5 for period covering the last week of May 2002. These new simulations incorporate all of the LAPS changes described earlier, in addition to the correction for the temperature bias. Work has begun to rerun all of the routine MM5 and WRF simulations with this correction applied. Results from these new simulations will be shown at the conference.

4. CONCLUSIONS AND FUTURE WORK

Results of this work provide hope for improving explicit short-range forecasts (0-12 h) of clouds and precipitation, even for convective environments, using state-of-the-art mesoscale NWP models combined with data assimilation techniques that make use of radar and satellite data. The computational efficiency of the system described in this paper makes it an affordable solution for local forecast office environments. Such an application of the LAPS diabatic initialization is now supporting operations in a demonstration mode at the Jacksonville National Weather Service Forecast Office as part of the NOAA Coastal Storms Initiative (Shaw et al., 2004).

The preliminary results using the WRF model provide an indication that it is rapidly maturing to the point of being a useful research and operational NWP model. It is anticipated that most of the future efforts at FSL with regard to the IHOP data will focus on the use of the WRF model.

The utility of the IHOP data archive will make it possible for FSL to test further enhancements to the LAPS diabatic initialization. An improved version of the Schultz microphysics has been developed to better handle sub-grid-scale cloudiness, including shallow convection. Additionally, the LAPS balance package is being modified to include a more complete thermodynamic representation of clouds and convection. These and future developments can be readily tested by reperforming the simulations spanning the IHOP period.

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